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A HEAT TRANSFER STUDY

OF A NUCLEAR ROCKET REACTOR

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A HEAT TRANSFER STUDY
OF A NUCLEAR ROCKET REACTOR

THESIS

Presented to the Faculty of the School of Engineering of

the Air Force Institute of Technology

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Master of Science

By

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Preface

In this study, I have made use of a digital computor to investigate and determine the temperature and pressure of hydrogen as it flows through a nuclear rocket reactor. The temperature of the fuel is calculated and the location of the "hot-spot" is also found. The reactor is assumed to be in steady-state operation and perfectly insulated with all heat generated passing to the hydrogen.

I have made use of empirical equations which include the effect of both temperature and pressure in calculating the value of the convective heat transfer coefficient for hydrogen. After thorough research, I believe that this is the only investigation of this nature that includes the effect of both temperature and pressure on this coefficient.

I have included the FORTRAN source program and the operating instructions in the appendices. The operating instructions are written for execution of the program on an IBM 7090 computer. However, since the program was originally used on an IBM 1620, only slight changes in the input-output statements should be required for adaptation to other computers capable of operating with FORTRAN.

As another appendix, I have included as a sample problem an optimization study to demonstrate the use of the program.

The investigation was suggested by Captain Charles J. Bridgman of the Department of Physics, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio. I would like to acknowledge my indebtedness to him for introducing me to the use of digital computers in mathematical studies and for his assistance and guidance throughout the preparation of this report. I would also like to acknowledge any errors or omissions as my own.

I hope that this investigation may prove beneficial in the design, development and implementation of a nuclear rocket and that it may help to advance the field of nuclear propulsion.

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List of Symbols

A_f	Hypothetical fuel cell cross-sectional area, ft^2
A_r	Reactor cross-sectional area, ft^2
A_t	Flow tube cross-sectional area, ft^2
F	Theoretical thrust, lb_f
I_{sp}	Specific impulse, sec
M	Temperature averaged molecular weight, lb_m/mole
N	Number of flow tubes
Nu	Nusselt Number
P	Power per unit length, BTU/ft
Pn	Prandtl number
P_t	Total power, megawatts
P_{pt}	Power per unit length per flow tube, BTU/ft
R	Specific gas constant, ft-lb_f/lb_m ^oR
R_o	Universal gas constant, ft-lb_f/mole ^oR
Rn	Reynolds number
S	Flow area surface per unit length, ft^2/ft
T	Absolute temperature, ^oR

T_c	Temperature of coolant at center of flow tube, $^{\circ}R$
T_m	Temperature of material at exterior periphery of fuel cell, $^{\circ}R$
T_s	Temperature of material at surface of flow tube, $^{\circ}R$
V	Velocity, ft/sec
V_c	Nozzle chamber velocity, ft/sec
V_e	Ideal nozzle exit velocity, ft/sec
W	Propellant mass flow rate, lb_m/sec
Z_{max}	Total reactor length, ft
c_p	Specific heat, BTU/lb_m $^{\circ}R$
d	Diameter, ft
d_i	Flow tube diameter, ft
d_o	Hypothetical fuel cell diameter, ft
d_r	Overall reactor diameter, ft
f_t	Turbulent friction factor
h	Connective heat transfer coefficient, BTU/hr ft^2 $^{\circ}R$
k	Thermal conductivity, BTU/hr ft $^{\circ}R$
p	Pressure, psia
$\dot{q}$	Heat generated per unit volume, BTU/hr ft^3
r	Radius, ft

r_i	Radius of flow tube, ft
r_o	Radius of hypothetical fuel cell, ft
η	Ideal Carnot cycle efficiency
μ	Absolute viscosity, $lb_m/$ ft sec
π	Pi, 3.1415927
ρ	Density, lb_m/ft^3

Abstract

A digital computer program was developed to investigate the coolant temperature and pressure and the material temperatures in a nuclear rocket reactor. The reactor uses hydrogen gas as the coolant and is operating under steady-state conditions.

The program is written in FORTRAN for execution on an IBM 7090 digital computer. Reactor geometry, input conditions of the coolant, power, power distribution, and reactor fuel thermal conductivity are variable input qualitites. The hydrogen is treated as a perfect gas and the reactor is assumed to be perfectly insulated. The coolant and material temperatures are determined by an iterative technique. The transport properties of hydrogen are computed by empirical formulas which include the effect of both temperature and pressure.

The FORTRAN source program, operating instructions, a sample problem and sample output data are included as appendices. The sample problem is a study which results in optimum propellant mass rate-of-flow and flow tube interior diameter for a given pressure drop and exit temperature.

A HEAT TRANSFER STUDY

OF A NUCLEAR ROCKET REACTOR

I. Introduction

The purpose of this study is to determine chamber temperature as accurately as possible for given reactor geometry and input parameters. The determination of fuel temperature and the pressure drop of the coolant through the reactor is also of importance. The large number of iterative calculations which will have to be made requires the use of digital computer techniques.

The use of nuclear power for propulsion has been an area of interest ever since the dawn of the atomic age in 1945. It is in current use as a source of propulsion for marine vessels. Present day investigation is concentrating on finding a means of applying nuclear power in the form of a rocket for the propulsion of space vehicles.

A brief analysis of the efficiency parameter, specific impulse, will demonstrate the potential superiority of nuclear rockets. Ideal specific impulse is defined as the theoretical thrust per propellant mass flow rate. Theoretical thrust is given by the equation:

$$F = \frac{W \cdot V_e}{g_c} \tag{1}$$

where F = Theoretical thrust

W = Propellant mass flow rate

V_e = Ideal nozzle exit velocity

g_c = Acceleration due to gravity

Specific impulse, I_{sp}, is given by the equation:

$$I_{sp} = \frac{F}{W} = \frac{V_e}{g_c} \qquad (2)$$

Therefore, specific impulse is proportional to the ideal nozzle exit velocity of the propellant.

The ideal nozzle exit velocity is found from the equation:

$$V_e^2 - V_c^2 = \frac{2kg_c}{k-1} \cdot \frac{R_o}{M} \cdot T \cdot \eta \qquad (3)$$

where V_c = Chamber velocity

k = Specific heat ratio

R_o = Universal gas constant

M = Temperature averaged molecular weight

T = Chamber temperature

η = Ideal Carnot cycle efficiency

Therefore if $V_e >> V_c$, it follows that

$$V_e \propto \frac{1}{\sqrt{M}} \qquad (4)$$

and

$$I_{sp} \propto \frac{1}{\sqrt{M}} \tag{5}$$

Thus, the lower the molecular weight of the propellant, the higher the specific impulse will be.

A nuclear rocket can use hydrogen, which has a molecular weight of approximately two pounds per mole, for the propellant. The lowest average molecular weight of the propellant gas for chemical rockets using hydrocarbon fuels such as liquid gasoline-oxygen is on the order of twenty to twenty-five pounds per mole. Therefore, the specific impulse of a nuclear rocket using hydrogen is on the order of three to one over the chemical rocket (Ref 2:20).

In Eq (3), the temperature term, T_c, occurs in the numerator. Therefore, the greater the chamber temperature of the gases, the greater will be the specific impulse and the thrust.

II. A Typical Nuclear Rocket

Before the heat transfer analysis is begun, a nuclear rocket will be discussed in general terms. This is necessary to obtain an understanding of the scope, limitations, and assumptions that will be employed.

General Description

A typical nuclear rocket is shown in Figure 1. The nuclear reactor is used to elevate the temperature of the hydrogen gas. The hydrogen is stored in the propellant tanks in the liquid state. By means of pumps and appropriate piping and control mechanisms, the hydrogen will be passed through the nozzle and reflector for purposes of cooling. The hydrogen will then be directed to the input side of the nuclear reactor. At this location, the hydrogen must be in the gaseous state. This will occur as a natural result of the nozzle and reflector cooling. The hydrogen will now pass through small flow passages in the nuclear reactor where the heat generated by the reactor will be transferred to and carried away by the hydrogen. The temperature of the hydrogen will be very high upon entering the chamber, thus yielding the large value needed in the numerator of Eq (3). The heat transfer process in turn keeps the reactor materials below their melting point.

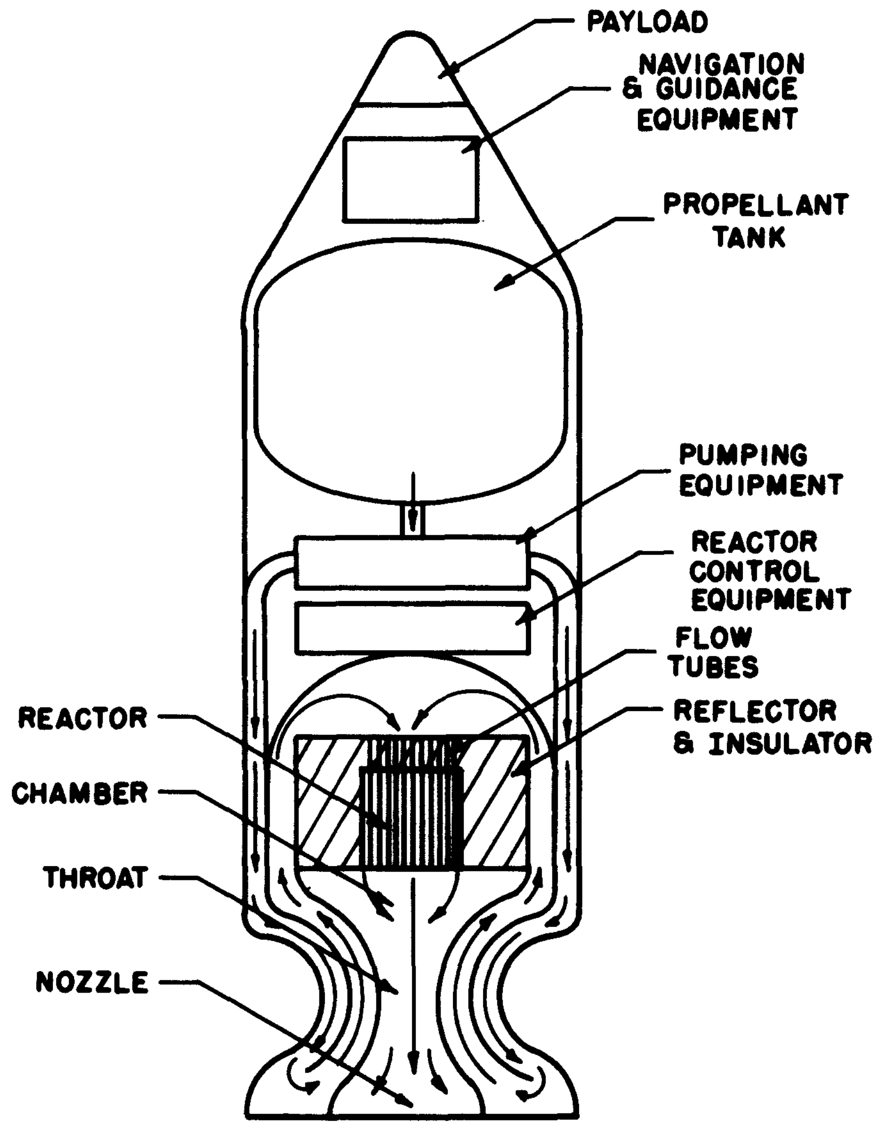


Fig. 1
Schematic of a Typical Nuclear Reactor Rocket.

After entering the chamber, the hydrogen passes through the nozzle where the very high exit velocity and thrust is obtained.

Reactor Geometry

A cylindrical geometry is assumed for this study. The passages through which the hydrogen flows will have a circular cross-section and be aligned parallel with the longitudinal axis of the reactor. The exterior of the reactor will have a reflector of appropriate size, shape and material to control the fission density and power distribution within the reactor as required by the design studies.

Should man be carried by the rocket, sufficient radiation shielding will also be required between the reactor and human domain.

Materials

The use of a nuclear reactor immediately suggests that very high temperature will be encountered. The materials that will be used for fuel, reflector, control, and structural support must be capable of withstanding the high differential-expansion and creep created by thermal stresses. Present day state of the art materials suggest the use of beryllium for the reflector and for the fuel, a cermet such as uranium oxide or uranium carbide embeded in a refractory metal. Of the refractories tungsten is the obvious choice because of its high

melting temperature (6600°R) (Ref 9:21-4). Thus the fueled region in this study will be assumed to have the heat transfer properties of pure tungsten. This is a definite assumption which ignores the presence of the uranium. The materials must also be resistant to radiation damage. The areas exposed to hydrogen must be able to resist the corrosion and embrittlement caused by the hydrogen (Ref 8:157).

Control

Associated systems such as guidance and control of the rocket through thrust-vectoring engines or vanes and stability gyroscopes will have to be included as in a rocket of any type. The control of the nuclear reactor itself, particularly during start-up and shut-down will require extensive measuring and interpretation networks. Power during steady state operation will be maintained at constant level through the use of shim rods and an automatic control programer (Ref 2:272).

Assumptions

It should now be apparent that a nuclear rocket is an extremely complex system composed of many interacting sub-systems. This investigation will be concerned only with the heat transfer occuring within the reactor under

steady state operation. Because even this sub-system is very complex, certain assumptions will have to be made so that the heat transfer problem may be analyzed.

The reactor is assumed cylindrical for geometrical compatibility with the rocket exterior. The flow passages, which will necessarily be very small, are assumed circular for ease in fabrication. It is further assumed that the reactor is perfectly insulated on the side and ends with all heat generated passed to and carried off by the hydrogen. This assumption with the requirement that the reactor be in steady state operation allows the use of one-dimensional steady heat conduction anulysis in the reactor fuel (Ref 5:35).

The power distribution within the reactor will be assumed to be uniform radially. This will be accomplished by variable loading of the reactor fuel combined with a suitable reflector on the side.

A flat radial power distribution will assure uniform flow through the reactor, thus yielding a maximum heat generation and subsequent transfer of the heat to the hydrogen throughout the reactor. Further, no discontinuities in pressure will exist in the nozzle chamber due to non-uniform flow. This also allows uniform flow passage size and subsequent ease in fabrication. Variation in the flow tube size as a function of radius would be extremely difficult to design even if there would be any practical advantage (Ref 2:164).

The coolant, normal hydrogen, will be in the gaseous state as it enters the reactor. It is assumed that pumps of sufficient capacity exist to accomplish the passage of the liquid hydrogen over the nozzle and reactor where the hydrogen is changed to the gaseous state. The hydrogen will be assumed to be the normal hydrogen gas composed of 75% ortho - 25% parahydrogen. Since the heat transfer characteristics of the two varieties differ only slightly and then, not until in the cryogenic range, this is a valid assumption (Ref 10:460).

Hydrogen remains in the diatomic state at atmospheric pressure to temperatures as high as 4460°R (Ref 2:34). Since coolant temperatures of this magnitude will not normally be encountered, and pressure will be much greater than atmospheric, no effects of dissociation will be considered.

The heat transfer to the hydrogen by means of thermal radiation from the reactor is negligible the absorptivity of hydrogen is on the order of zero (Ref 1:433, 812). Therefore, the effect of radiation in the heat transfer analysis will not be considered.

Hydrogen may be treated as a perfect gas. Since the temperature and pressure that will be encountered in the nuclear reactor are not low compared with critical conditions, this is a valid assumption (Ref 9:41) and the perfect gas law,

$$p = \rho RT \tag{6}$$

may be safely employed.

The last assumption that will be necessary before beginning the heat transfer analysis is that the gas velocity in the collecting chamber above the reactor is zero. This assumption is justifiable on the basis that the volume of the collecting chamber will be large compared with the volume of the flow tubes.

III. The Heat Transfer Theory

The necessary heat transfer equations can now be developed from one; dimensional steady heat flow theory. However, some general background information must be given first.

Determination of Fuel Cell Diameter

As described previously, the nuclear reactor used for heat generation will have circular flow tubes parallel with the longitudinal axis of the reactor. Since the power distribution has been assumed uniform radially, it will be most accurate to work with one representative tube and investigate the heat transfer which takes place. The same amount of heat will be transferred to the hydrogen in each tube. Therefore, a hypothetical fuel cell will be defined. Each flow tube lies at center of one of the fuel cells.

The cross-sectional diameter of the hypothetical fuel cell is determined by the following analysis. Since the number of flow tubes will be very large, the approximation is very close to actual conditions. The area of the reactor given by

$$A_r = \frac{\pi \cdot d_r^2}{4} \tag{7}$$

the area of one fuel cell is

$$A_f = \frac{\pi \cdot d_o^2}{4} \tag{8}$$

where the fuel cell diameter, d_o, is to be found.

If the cross-sectional area of one cell is multiplied by the number of flow tubes and this area placed equal to the reactor area, the diameter of each hypothetical cell may be found from

$$d_o^2 = \frac{d_r^2}{N} \tag{9}$$

this approximation is illustrated in Fig. 2 for only seven tubes. The actual reactor will contain at least 10,000 such tubes. In the limit, the shaded area will not exist at all since the approximation requires the tube cross-sectional area to be equal to the reactor cross-sectional area.

Nomenclature for the Incremental Fuel Cell

A typical fuel cell increment of volume is illustrated in Fig. 3. The coolant temperature, T_c, is the temperature at the center of the flow tube. The surface temperature, T_s, is the temperature at the inside diameter of the fuel cell, while the material temperature, T_m, is the temperature at the exterior of the fuel cell. Each fuel cell will be taken as independent of all others. The amount of heat generated, $\dot{q}$, within each increment of volume along the tube will increase the temperature of the hydrogen within that volume.

Radial Temperature Distribution within the Fuel Cell Material

By use of one-dimensional steady flow heat conduction analysis, the temperature as a function of radius may be determined (Ref 5:65).

The basic equation is: $$\frac{d}{dr}\left(r\frac{dt}{dr}\right) = \frac{\dot{q}}{k}\, r \tag{10}$$

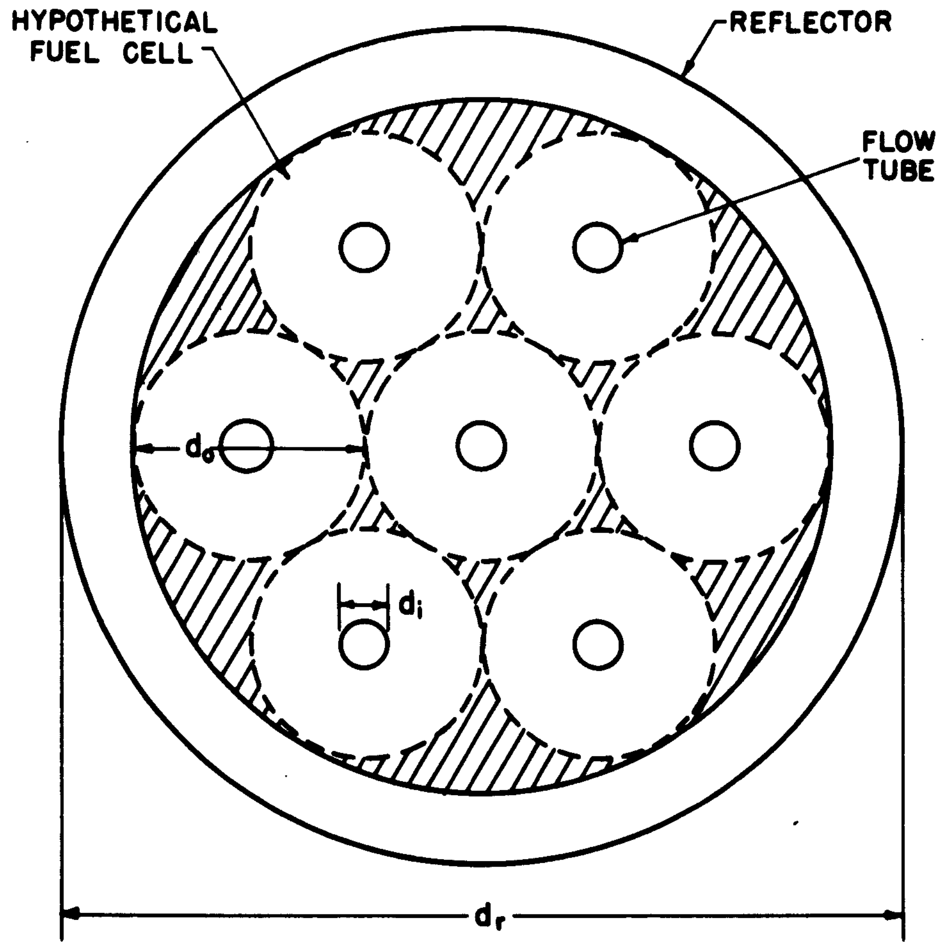


Fig. 2

Axial View of a Simplified Nuclear Reactor Illustrating Fuel Cell Approximation.

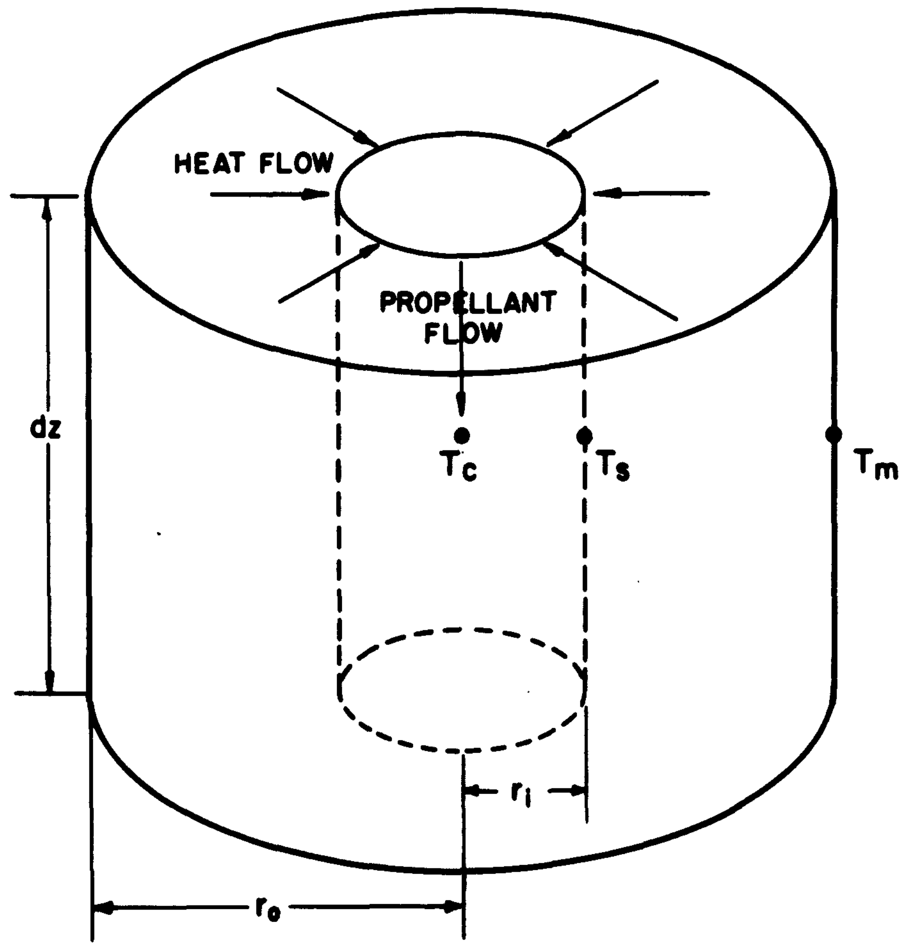


Fig. 3

Incremental Fuel Cell Volume

Integrating:

$$r\frac{dT}{dr} = -\frac{\dot{q}r^2}{2k} + C_1$$

and

$$\frac{dT}{dr} = -\frac{\dot{q}r}{2k} + \frac{C_1}{r}$$

Therefore:

$$T(r) = -\frac{\dot{q}r}{4k} + C_1 \ln r + C_2$$

But

$$\frac{dt}{dr} = 0 \text{ at } r = r_o$$

$$\therefore C_1 = \frac{\dot{q}r_o^2}{2k}$$

$$T(r) = -\frac{\dot{q}r^2}{4k} + \dot{q}\frac{r_o^2}{2k} \ln r + C_2$$

But $\quad T = T_m$ at $r = r_o$

or

$$T_m = -\frac{\dot{q}r_o^2}{4k} + \frac{\dot{q}r_o^2}{2k} - \ln r_o + C_2$$

$$\therefore C_2 = T_m + \frac{\dot{q}r_o^2}{4k} - \frac{\dot{q}r_o^2}{2k} \ln (r_o)$$

And

$$T(r) = -\frac{\dot{q}r^2}{4k} + \frac{\dot{q}r_o^2}{2k} \ln (\frac{r}{r_o}) + \frac{\dot{q}r_o^2}{4k} + T_m$$

at $\quad r = r_i,\ T(r) = Ts$

Therefore

$$T_m = T_s - \frac{\dot{q}}{4k}(r_o^2 - r_i^2) - \frac{\dot{q}r_o^2}{2k} \cdot \ln (\frac{r_i}{r_o})$$

which may be written in terms of the diameter as

$$T_m = T_s + \frac{\dot{q}}{4k}\left[\frac{2d_o^2}{4}\ \ln\left(\frac{d_o^2}{d_i^2}\right) - \frac{(d_0^2 - d_i^2)}{4}\right]$$

or

$$T_m = T_s + \frac{\dot{q}}{16k}\left[d_o^2\ \ln\left(\frac{d_o^2}{d_i^2}\right) - (d_o^2 - d_i^2)\right] \qquad (11)$$

This equation will be used as the basic equation for the determination of the fuel temperature given the surface temperature of the tube and thermal conductivity of the fuel.

Convective Heat Transfer within the Coolant

The heat generated within the fuel cell, $\dot{q}$, is now passed to the hydrogen in the flow tube. The quantity, $\dot{q}$, is a constant in the incremental volume under consideration and the convective heat transfer relationships (Ref 5:233) may be written as

$$\dot{q} = S \cdot h\,(T_s - T_c) \qquad (12)$$

The apparent simplicity of this equation may prove misleading. The convective heat transfer coefficient is a function of the Reynolds number, the Prandtt number and the term Tc/Ts (Ref 7:29).

The Nusselt equation which will be used to determine the heat transfer coefficient is

$$Nu = (0.023)\,(R_n)^{.8}\,(P_n)^{.4}\,(T_c/\,T_s)^{.3} \qquad (13)$$

In experimental results obtained by J. R. McCarthy and H. Wolf of the Rocketdyne Corp., Canoga Park, Calif., this equation yielded accuracy within ±8% under high pressure, high Reynolds number flow conditions (Ref 7). The flow in a nuclear rocket reactor is in accordance with these constraints and Eq (13) will be used.

The Nusselt number, Nu , may be written, $\frac{hd}{k}$, where d is the hydraulic diameter. For a hollow cylinder, the hydraulic diameter is equal to the actual diameter (Ref 8:198).

The term k is the thermal conductivity of the gas evaluated at the bulk temperature. The bulk temperature for gas flowing in a tube in the turbulent regime may be taken as the central temperature. This is because the cross-sectional velocity in turbulent flow is uniform across the tube, rather than parabolic as in laminar flow. The thermal conductivity is determined empirically as follows (Ref 7:79)

$$k = k_o x \tag{14}$$

For $\left(150R < T_c < 400^\circ R\right)$

$$k_o = 2.875 \times 10^{-4} \cdot (T_c)^{0.944}$$

For $\left(400R < T_c < 600^\circ R\right)$

$$k_o = 4.94 \times 10^{-4} \cdot (T_c)^{0.852}$$

For $T_c > 600^\circ R$

$$k_o = 5.951 \times 10^{-4} (T_c)$$

And for $150^\circ R < T_c < 230^\circ R$

$0 \text{ psia} < p < 1000 \text{ psia}$

$$x = (4.98 \times 10^{-4} \cdot (100/T_c)^{2.584} + 4.338 \times 10^{-6}) + 1$$

For $T_c > 230^\circ R$

and $p < 550$ psia

$$x = 6.18 \times 10^{-5} \cdot p + 1$$

For $T_c > 230^{\circ}R$

and 550 psia < p < 1500 psia

$$x = 3.4 \times 10^{-5} \cdot p + 1.016$$

For $T_c > 230^{\circ}R$

and for 1500 psia < p < 2000 psia.

$$x = 5.9 \times 10^{-6} \cdot p + 1.058$$

Above $1260^{\circ}R$, the data above are extrapolated.

The Reynold's number is, by definition

$$Rn = \frac{V \cdot d_i \cdot \rho}{\mu} \tag{15}$$

The velocity, V, may be found from the continuity equation,

$$\dot{m} = \rho V A_t \tag{16}$$

and the density may be calculated from the ideal gas equation, Eq (6).

The diameter, d_i , of course, is given, but empirical formulas must be used to find the absolute viscosity, μ, (Ref 7:78).

The viscosity may also be determined from empirical formulas as follows.

$$\mu = \mu_o x \tag{17}$$

For $T_c < 1980^{\circ}R$

$$\mu_o = \frac{.057848 \times 10^{-6} \cdot (T_c/1.8)^{1.5} \; ((T_c/1.8) + 650.39)}{((T_c/1.8) + 19.55) \; ((T_c/1.8) + 1175.9)}$$

If $T_c > 1980^{\circ}R$

$$\mu_o = 0.8226 \times 10^{-7} \cdot (T_c)^{0.68}$$

For $T_c < 200^\circ R$

and $p < 500$ psia

$$x = 2 \times 10^{-4}. (1.218 ((100/T_c{}^{2.86}) - 1.92 \times 10^{-3}) .6 + 1$$

For $T_c < 200^\circ R$

and $p > 500$ psia

$$x = 2 \times 10^{-4}. (2.0918 ((100/T_c)^{1.81}) + 0.0282) \ (p-90) + .967$$

If $200^\circ R < T_c < 300^\circ R$

and $p < 500$ psia

$$x = 2.0 \times 10^{-4} \ (.2554 ((100/T_c)^{.469}) - .01428) \ p + 1$$

If $200^\circ R < T_c < 300^\circ R$

and $p > 500$ psia

$$x = 2 \times 10^{-4} (7.83 ((100/T_c)^{3.7}) - .01141) (p-450) + 1.01$$

If $300^\circ R < T_c < 400^\circ R$

$$x = 2 \times 10^{-4} \ (.3175 \ ((100/T_c)^{2.0}) - .00115) \ p + 1$$

For $400^\circ R < T_. < 100^\circ R$

$$x = 2 \times 10^{-4} \ (.129 - 1.29 \times 10^{-4} \ T_c) \ p + 1$$

And for $T_c > 100^\circ$ R

$$x = 1.0$$

These values are extrapolated above $1980^\circ R$.

The Prandtl number is given by the empirical relations which follow (Ref 7:81)

For $T_c < 500^\circ R$

and $p_c < 1000$ psia

$$Pn = 0.715 + 8\ 191 \times 10^5\ ((p/100)^{.504})\ (500 - T_c) \tag{18}$$

For $500^\circ R < T_c < 1200^\circ R$

$$Pn = 1.275\ (T_c^{-.0935})$$

For $T_c > 1200^\circ R$

$$Pn = .66$$

These values are extrapolated above 1440°R.

By use of the Nusselt equation and the empirical formulas for absolute viscosity, Prandtl number and thermal conductivity, the value of the corrective heat transfer coefficient may be determined. The surface temperature is determined from Eq (12) as below

$$T_s = T_c + \frac{\dot{q}}{h\ .\ S} \tag{19}$$

Determination of Coolant Temperature at next Incremental Volume.

To determine the temperature of the coolant at the next incremental volume, the relationships (Ref 2:125)

$$\dot{q} = W\ c_p\ \Delta T_c \tag{20}$$

must be used. Before this is possible though, the value of the c_p must be found.

The specific heat, c_p, is also found by the use of empirical relationships (Ref 7:80)

For $T < 414^\circ R$ (21)

$$c_p = 71.7523 - 89.607 \log_{10} T_c + 38.0295 (\log_{10} T_c)^2 - 5.26605 (\log_{10} T_c)^3$$

If $T_c > 414^\circ R$

$$c_p = -77.2672 + 81.7961 (\log_{10} T_c - 27.6505 (\log_{10} T_c)^2 + 3.11872 (\log_{10} T_c)^3$$

The values of c_p are extrapolated above $1808^\circ R$.

Since W, the propellant mass rate of flow is given and is constant, the temperature may be found from $T_{(i+1)} = T_{(i)} + \frac{\dot{q}}{W \cdot c_p}$

Determination of Pressure Drop

Due to the velocity in the flow tube, frictional resistance to flow is created (Ref 8:171). To determine the pressure at the next incremental volume, the pressure drop through the incremented volume caused by friction will have to be found. The equation

$$p = \cdot f_t \cdot (L/d_i) \cdot (V^2/2g) \tag{22}$$

will give the value of the pressure drop. The friction factor for turbulent flow, f_t is found from the equation

$$f_t = .184/(R_n)^{.2} \tag{23}$$

The density and velocity of the gas at the next incremented volume may now be determined.

Summary: All of the equations necessary for the writing of the digital computer program are now available. In the next Chapter, how these equations are put together to obtain the exit temperature, exit pressure and maximum material temperature will be discussed.

IV. The FORTRAN Programming of the Nuclear Rocket Reactor Heat Transfer Study, "HY NUK ROK"

General Information

The heat transfer equations discussed in the last chapter were programmed in FORTRAN for the IBM 7090 digital computer. This chapter will discuss the programming of "HY NUK ROK" by sections with the aid of the generalized flow chart given in Figure 4. Operating instructions and a sample problem will be found in Appendices B and C.

Reactor Data

This portion of the program reads the length and diameter of the reactor, the diameter and number of flow tubes, and the input pressure and temperature of the hydrogen. The mass flow rate, power of the reactor, and thermal conductivity of the fuel are now read. The iteration tolerance is then read followed by the reactor power distribution data. These quantities may be taken from reactor specifications or varied by the user in design studies.

Reactor Power and Power Distribution

The total reactor power in megawatts and a graph of the local-to-average

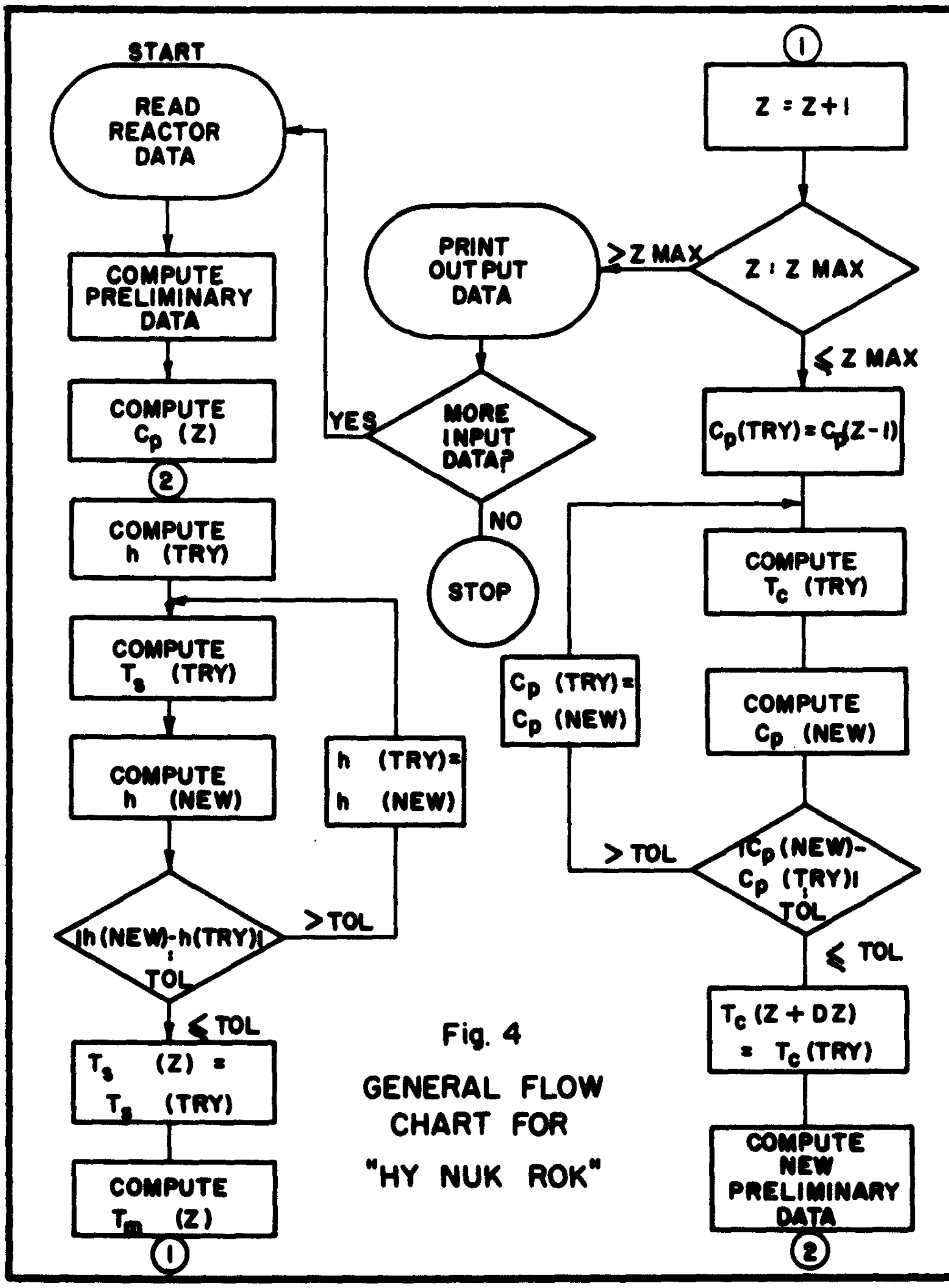


Fig. 4

GENERAL FLOW CHART FOR "HY NUK ROK"

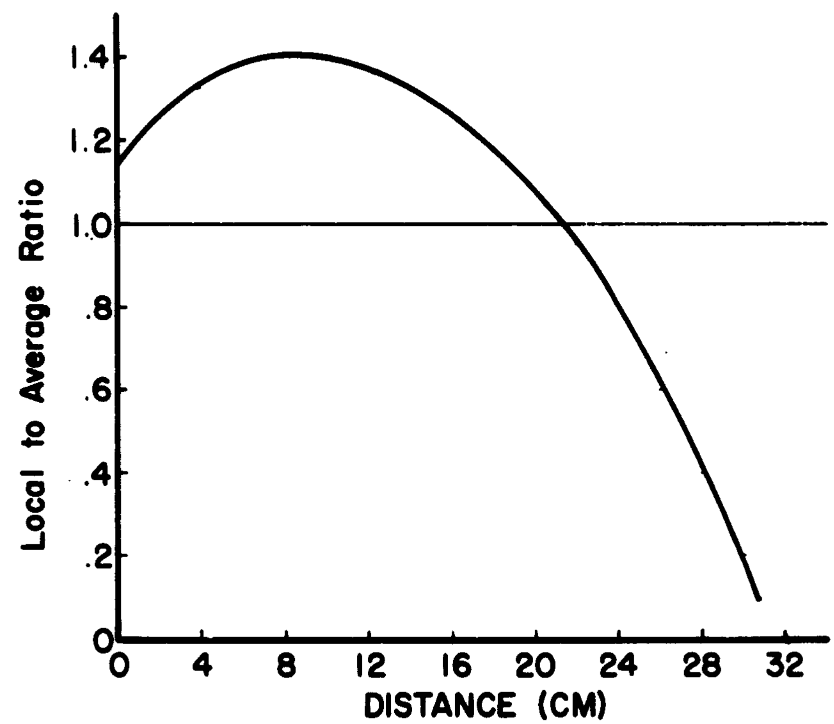
fission density distribution as a function of length for the reactor under study will be provided by the manufacturer and is accepted as input data by the program. The total power and local-to-average fission density distribution may be varied by the engineer at will if the program is used in design studies.

To determine the average power per unit length per flow tube, the following equation is used.

$$P_{pt} = \frac{P_t}{Z_{max} N} \tag{24}$$

This computation is accomplished automatically in the course of the program.

The power generated at any increment of volume along the tube may be determined by multiplying the average power per unit length per flow tube by the local-to-average ordinate at the station under consideration. A graph of the local-to-average fission density distribution is given in Figure 5. The program provides read-in of this curve by specifying the number of ordinates to be read, the distance between the ordinates to be read and the value of the ordinate. Since local-to-average fission density distribution curves are given with centimeters as the unit of length, the program provides for read-in in centimeters and converts automatically to units of feet. The propulsion engineer normally works with the British system of units. The ordinates which the computer will read are given below the graph in Figure 5. The



DIST(CM)	0	2	4	6	8	10	12	14	16
LOCAL-TO-AVERAGE RATIO	1.15	1.25	1.32	1.38	1.40	1.39	1.33	1.30	1.25

DIST(CM)	18	20	22	24	26	28	30	30.42
LOCAL-TO-AVERAGE RATIO	1.15	1.08	.95	.75	.60	.40	.20	.10

Fig. 5

A Typical Local-to-Average Fission Density Distribution

ordinate at any point along the flow tube is then computed by straight linear interpolation using a truncation technique. Since power is proportional to fission-density distribution, the local power generated at any increment is obtained then by multiplication of the average power by the ordinate at that point.

Preliminary Calculations

This portion of the program computes various quantities that will be constant or that must be computed for initializing purposes.

This includes input density of the hydrogen and input specific heat. The density is computed by means of the perfect gas equation and the specific heat is computed by means of Eq (21).

The square of the hypothetical fuel volume diameter is computed in this section and the square of the inside diameter and the cross-sectional area of a flow tube is also computed.

The length of an incremental volume is determined by dividing the total length of the reactor by 100. The propellent mass flow per tube and the velocity in the first increment of the flow tube is determined.

Determination of Surface Temperature

The surface temperature of the flow tube in the first increment is calculated by first computing the absolute viscosity by means of the empirical

equation given in Chapter III as Eq (17).

Since the tube diameter, velocity, density, and viscosity are now known, the Reynolds number at the first station is calculated.

Using the empirical equation for thermal conductivity of the hydrogen given in Eq (14), this quantity is computed. The Prandth number of the hydrogen is then found by use of the empirical equations in Eq (18).

Since thermal conductivity, Reynolds number, Prandth number, and the tube inside diameter is known, a trial value of the heat transfer coefficient, HTRY, is found. This trial value is found without use of the term $(T_c / T_s)^{0.3}$, since no value for the surface temperature is yet known. (In essence, the computation of the trial value of h is computed by setting T_s equal to T_c).

A trial surface temperature, TSTRY, is then found by means of Eq (12). Since

$$h = f(T_s) \tag{25}$$

and

$$T_s = f(h)$$

an iteration technique is necessary for the solution of T_s. This is accomplished by now finding a trial value of h, HNEW, by using the value obtained for T_s. HTRY is then subtracted from HNEW and the absolute value of the difference is compared with an iteration tolerance, TOL. The iteration tolerance is specified by the user. If the absolute value of the difference is less than the tolerance, the equation given in Eq (25) are considered as satisfied and the surface

temperature at the station under consideration is set equal to the trial temperature used in the last iteration. If the difference is greater than the tolerance, HTRY is replaced by HNEW and a new trial surface temperature is computed. This loop is continued until the difference converges to the required tolerance as described above.

Temperature of the Fuel

The material temperature at the exterior periphery of the hypothetical fuel cell is then computed by means of Eq (11). It should be noted that the thermal conductivity is temperature dependent. However, no relationship is known at present and a close approximation is obtained by using the thermal conductivity of the fuel diluent and entering this value as a constant to be read as input data.

The maximum fuel cell periphery temperature or "hot-spot" temperature, TMAX, is also determined and printed as output data.

After the fuel temperature is computed, the friction factor for the increment is found by means of Eq (23).

At this point, the length is incremented by DZ and the new length is compared to the total length. If this value obtained is greater than the total length, the computations are terminated and the pressure, coolant temperature, surface temperature and material temperature are printed as found in Appendix D. The program then checks to determine if more input data is to be read and if not, stops.

If there is more data, the computation procedure continues with the new problem.

If the new length is less than or equal to the reactor length, the pressure drop through the last increment is found by means of Eq (22) and the pressure at the new increment is calculated by subtracting the pressure drop from the previous pressure.

By means of linear interpolation, the power generated at the new increment is computed and stored in memory as QZ.

Computation of New Coolant Temperature

Since

$$T_c = f(c_p) \tag{26}$$

and

$$c_p = f(T_c)$$

an iterative technique must again be employed. By using the last value of the specific heat, c_p, a trial value is obtained, CPTRY. Using this value of c_p and Eq (20), a value for the coolant temperature at the next increment is found. Using this value of T_c, and the empirical equation for c_p, a value for the specific heat at the next increment, CPNEW, is obtained. The program then subtracts CPTRY from CPNEW and compares the absolute value of the difference with the iteration tolerance, TOL. If this difference is greater than the tolerance, the trial value, CPTRY, is replaced by CPNEW and the iteration is continued until the absolute value of the difference is less than or equal to the tolerance. When this requirement is complied with, the transcendental equations given by Eq (26) are satisfied and the temperature of the coolant at the new incrment is

placed equal to TCNEW while the specific heat at the new increment is placed equal to CPNEW.

The density and velocity at the new increment are now computed and the process of determining the surface and fuel temperature, then advancing and then determining the new coolant temperature is continued until the entire tube is traversed at which time the coolant pressure, coolant, surface and fuel temperature is printed by increment as described previously .

Summary

This Chapter described the method by which the equations from the heat transfer theory were combined to form the computer program. The FORTRAN source program is included as Appendix A.

V. Calculated Results

The program described in the last chapter was employed to make several sets of calculations for varying input parameters, some of which are found in Appendix C as a sample problem and offer some direction for the design of a nuclear rocket. Time limitations precluded a complete design optimization. The primary contribution of this report was the creation of the means by which an optimization might be carried out. Trends, however, became obvious after just a few runs. The analysis of the trends recognized by this author for a fixed reactor geometry, power, and power distribution follow.

Flow Tube Diameter

As the flow tube diameter is decreased, the hot spot temperature is decreased. However, decreasing the flow tube diameter results in an increased pressure drop. The lower limit is reached when the pressure drop through the core becomes prohibitive for a given mass rate of flow. A large pressure drop through the core of the reactor presents both structural and thrust dilution problems.

Mass Rate of Flow

As the coolant mass rate of flow is increased, the hot spot temperature is decreased. However, the coolant exit temperature is also decreased, while the pressure drop through the reactor core increases. The upper limit to the mass rate of flow then is the lowest acceptable coolant exit temperature

coupled with an acceptable pressure drop.

Additional Trends

As the input temperature of the hydrogen increases, the hot spot temperature and the coolant exit temperature will increase. The upper limit to the coolant inlet temperature is the maximum allowable hot-spot temperature.

As the number of flow tubes are decreased, the hot spot temperature again increases, while the coolant exit temperature also increases. The lower limit to the number of flow tubes is again the hot-spot temperature of the reactor.

There are other input quantities such as power, and power distribution, input pressure, reactor length, and reactor diameter which could be varied, each of which affect the pressure drop, hot-spot and coolant exit temperature. The two most important parameters, however, appear to be flow tube diameter and mass rate-of-flow.

VI. Conclusions, Limitations and Recommendations

Conclusions

The heat transfer study has resulted in a digital computer program which may be used in the design, analysis and development of nuclear rockets. The coolant exit temperature, maximum fuel temperature and pressure drop of nuclear rockets in the design stage may be verified and adjustments in the geometry or input variables may be made as necessary.

Limitations

Although this study represents the best possible efforts to obtain overall accuracy, many assumptions were necessary to effect a solution. The final measure of accuracy will be actual experimental verification. In a field as new as nuclear propulsion, where no nuclear rocket is yet in the test stage, experimental verification is now impossible. When experimental data does become available, the actual data should provide agreement with the heat transfer analysis within a range of error and the program may then be adjusted accordingly.

Recommendations

The heat transfer analysis was for the steady-state operating conditions only. Start-up and shut-down of the reactor should constitute the next phase of investigation. A study of this nature should be possible by time varying

the power and propellant-mass flow rate. The computer program here presented could effectively be used as the basis for the time dependent study.

An investigation of this nature would be required to use a nuclear rocket for such missions as orbital transfer and interplanetary exploration.

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Appendix A

The FORTRAN Source Program for "HY NUK ROK"

On the following pages, the Source Program for "HY NUK ROK" will be found. The symbols follow the program description and generalized flow chart given in Chapter 4.

```
C     HY NUK ROK
      DIMENSION P(102),TC(102),R(102),Z(102),V(102)
      DIMENSION TS(102),TM(102),FF(102),CP(102),D(100)
506   READ INPUT TAPE 2,500,ZMAX,DIR,FT,DII,PIN,TIN
500   FORMAT(6E12.0)
      READ INPUT TAPE 2,500,W,POW,TKM,TQL,TOTZ,DIST
      READ INPUT TAPE 2,600,N
600   FORMAT(I4)
      READ INPUT TAPE 2,500,(D(J),J=1,N)
      RIN=(PIN*144.)/(766.4*TIN)
      DIOSQ=(DIR**2.)/FT
      DIISQ=DII*DII
      AREA=3.1415927*DIISQ/4.
      DZ=ZMAX/100.
      WPT=W/FT
      POWPT=POW*3.412E+06/(ZMAX*FT)
      I=1
      Z(I)=0.
      P(I)=PIN
      TC(I)=TIN
      R(I)=RIN
      IF (414.-TIN)47,47,46
46    A=71.7523-((89.607)*(.43429)*(LOGF(TIN)))
      B=38.0295*((.43429*LOGF(TIN))**2)
      C=(-5.26605)*((.43429)*(LOGF(TIN)))**3
      GO TO 48
47    A=-77.2672+((81.7961)*(.43429)*(LOGF(TIN)))
      B=-27.6505*((.43429*LOGF(TIN))**2)
      C=(+3.11872)*((.43429*LOGF(TIN))**3)
48    CP(I)=A+B+C
      QZ=D(I)*POWPT
1     V(I)=WPT/(R(I)*AREA)
      IF (1980.-TC(I))3,3,2
2     AVN   =.5748E-6*((TC(I)/1.8)**1.5)*((TC(I))/(1.8)+650.39)
      AVD   =(((TC(I))/(1.8)+19.55 )*(((TC(I))/(1.8))+1175.9)
      AV    =AVN/AVD
      GO TO 4
3     AV    =(.8226E-7)*(TC(I)**.68)
4     IF (200.-TC(I))8,8,5
5     IF (500.-P(I))7,7,6
6     X     =.0002*(1.218*((100./TC(I))**2.86)-.00192)*P(I)+1.
      GO TO 17
7     X     =.0002*(2.0918*((100./TC(I))**1.81)+.0282)*(P(I)-90.)+.967
      GO TO 17
8     IF (300.-TC(I))12,12,9
9     IF (500.-P(I))11,11,10
10    X     =.0002*(.2554*((100./TC(I))**.469)-.01428)*P(I)+1.
      GO TO 17
11    X     =.0002*(7.83*((100./TC(I))**3.7)-.01141)*(P(I)-450.)+1.01
      GO TO 17
12    IF (400.-TC(I))14,14,13
13    X     =.0002*(.3175*((100./TC(I))**2.)-.00115)*P(I)+1.
      GO TO 17
14    IF (1000.-TC(I))16,16,15
15    X=.0002*(.129-(.000129*TC(I)))*P(I)+1.
```

```
      GO TO 17
16    X=1.
17    AV=AV*X
      RN   =DII*V(I)*R(I)/AV
      RN8=RN**.8
      IF (400.-TC(I))19,19,18
18    TK   =.0002875*(TC(I)**.944)
      GO TO 22
19    IF (600.-TC(I))21,21,20
20    TK   =.000494*(TC(I)**.852)
      GO TO 22
21    TK   =.0005951*(TC(I)**.821)
22    IF (230.-TC(I))24,24,23
23    Y   =(.000498*((100./TC(I))**2.584)+4.338E-6)*P(I)+1.
      GO TO 29
24    IF (550.-P(I))26,26,25
25    Y=6.18E-5*P(I)+1.
      GO TO 29
26    IF (1500.-P(I))28,28,27
27    Y   =3.4E-5*P(I)+1.016
      GO TO 29
28    Y   =5.9E-6*P(I)+1.058
29    TK=TK*Y
      IF(500.-TC(I))101,101,100
100   PN=.715+.8191E-04*((P(I)/100.)**.504)*(500.-TC(I))
      GO TO 104
101   IF(1200.-TC(I))102,102,103
103   PN=1.275*(TC(I)**(-.0935))
      GO TO 104
102   PN=.66
104   PN4=PN**.4
      H1=(.023/DII)*TK*RN8*PN4
      HTRY=H1
105   RF=QZ/(HTRY*3.1415927*DII)
      TSTRY=TC(I)+RF
      HNEW=H1*((TC(I)/TSTRY)**.3)
      IF(ABSF(HNEW-HTRY)-TOL)301,301,300
300   HTRY=HNEW
      GO TO 105
301   TS(I)=TSTRY
      RMN=QZ*(DIOSQ*LOGF(DIOSQ/DIISQ)-(DIOSQ-DIISQ))
      RMD=4.*TKM*(DIOSQ-DIISQ)*3.1415927
      TM(I)=TS(I)+(RMN/RMD)
      IF(I-1)210,210,209
209   IF(TM(I)-TM(I-1))210,210,200
200   TMAX=TM(I)
210   FF(I)=.184/(RN**.2)
      I=I+1
      Z(I)=Z(I-1)+DZ
      IF(Z(I)-ZMAX)211,211,36
211   DP=R(I-1)*FF(I-1)*DZ*(V(I-1)**2)/(DII*64.4*144.)
      P(I)=P(I-1)-DP
      DELZ=DIST*ZMAX/TOTZ
      J=Z(I)/DELZ+1.
      IF(J-N)405,406,406
406   Y=D(J)
```

```
      GO TO 404
405   IF((N-1)-J)402,402,401
401   WY=J-1
      FRAC=Z(I)-WY*DELZ
      GO TO 403
402   EX=N-2
      TOP=EX*DIST
      FRAC=Z(I)-EX*DELZ
      DELZ=(TOTZ-TOP)/TOTZ
403   FAC=FRAC/DELZ
      Y=D(J)+FAC*(D(J+1)-D(J))
404   QZ=Y*POWPT
      CPTRY=CP(I-1)
30    TCNEW=TC(I-1)+QZ*DZ/(CPTRY*WPT*3600.)
      IF (414.-TCNEW)32,32,31
31    A=71.7523-((89.607)*(.43429)*(LOGF(TCNEW)))
      B=38.0295*((.43429*LOGF(TCNEW))**2)
      C=(-5.26605)*((.43429)*(LOGF(TCNEW)))**3
      GO TO 33
32    A=-77.2672+((81.7961)*(.43429)*(LOGF(TCNEW)))
      B=-27.6505*((.43429*LOGF(TCNEW))**2)
      C=(+3.11872)*((.43429*LOGF(TCNEW))**3)
33    CPNEW=A+B+C
      IF(ABSF(CPNEW-CPTRY)-TOL)35,35,34
34    CPTRY=CPNEW
      GO TO 30
35    TC(I)=TCNEW
      CP(I)=CPNEW
      R(I)=(P(I)*RIN*TIN)/(TC(I)*PIN)
      GO TO 1
36    PEX = P(I-1)
      TEX=TC(I-1)
      WRITE OUTPUT TAPE 3,41
41    FORMAT(1H1/////19H         GA/PHYS/63-2)
      WRITE OUTPUT TAPE 3,43,ZMAX,DIR,FT,DII
43    FORMAT(12H8         ZMAX=,F7.3,3X,4HDIR=,F7.3,3X,3HFT=,F8.0,3X,
     14HDII=,F10.8)
      WRITE OUTPUT TAPE 3,50,PIN,TIN,W,POW
50    FORMAT(12H          PIN =,F7.0,3X,4HTIN=,F7.0,3X,3HW =,F8.0,3X,
     14HPOW=,F10.4)
      WRITE OUTPUT TAPE 3,51,TKM,TOL
51    FORMAT(12H          TKM =,F7.2,3X,4HTOL=,F7.4)
      WRITE OUTPUT TAPE 3,53,PEX,TEX,TMAX
53    FORMAT(11H8         PEX=,F10.4,7X,4HTEX=,F10.4,7X,5HTMAX=,F10.4)
      WRITE OUTPUT TAPE 3,52
52    FORMAT(9H8        DZ,9X,1HP,13X,2HTC,12X,2HTS,12X,2HTM//)
      WRITE OUTPUT TAPE 3,44,(I,P(I),TC(I),TS(I),TM(I),I=1,30)
44    FORMAT(1H ,I8,4F14.4)
      WRITE OUTPUT TAPE 3,41
      WRITE OUTPUT TAPE 3,52
      WRITE OUTPUT TAPE 3,44,(I,P(I),TC(I),TS(I),TM(I),I=31,65)
      WRITE OUTPUT TAPE 3,41
      WRITE OUTPUT TAPE 3,52
      WRITE OUTPUT TAPE 3,44,(I,P(I),TC(I),TS(I),TM(I),I=66,101)
      GO TO 506
      END(1,0,0,0,0,0,1,0,0,1,0,0,0,0,0)
```

Appendix B

Operating Instructions for "HY NUK ROK"

The operating instructions that follow are for a typical IBM 7090 digital computer. Any digital computer capable of working with FORTRAN should prove compatible with necessary changes made in the input-output statements in the source program and perhaps a modification to the data card format.

The compilation time on the IBM 7090 is approximately fifty seconds while the execution time per problem is approximately one minute. The program will also operate satisfactorily with the necessary changes in the input-output statements on an IBM 1620. The compilation time, however, is approximately 45 minutes while program execution requires an average of 55 minutes.

The first step to be followed for execution on the IBM 7090 is to have the Source Program as given in Appendix A punched on cards. If data is not yet prepared for problem execution, an object program may be obtained by having an identification card punched and having the program run for compilation only. Since identification cards vary with every computer installation, the user will have to obtain the necessary identification card format from the computer facility to be used. A program listing as in Appendix A and an object program deck will be obtained from the compilation run.

The first card contains reactor geometry data and the input pressure and temperature of the hydrogen. The reactor geometry includes the overall length, overall diameter, number of flow tubes and flow tube inside diameter. The data for the first card should be entered as follows: Columns 1 - 12, the reactor overall length, feet; columns 12 - 24, the overall reactor diameter, feet; columns 25 - 36, the number of propellant flow tubes; columns 37 - 48, the flow tube diameter, feet; columns 49 - 60, the propellant input pressure, psia; columns 61- 72, the propellant input temperature, $^{\circ}$R. The data for this and all other cards may appear anywhere in the columns provided.

The second card contains the propellant mass rate of flow, the total reactor power, the thermal conductivity of the fuel, and the iteration tolerance. The second card also contains two entries that will be read from the local-to-average fission density distribution graph. The program has been constructed to accept any system of units for the reading-in of these items. The only requirement is that the term TOTZ and DIST. be in the same system of units. TOTZ represents the total reactor length and DIST is the distance between ordinates where the fission density distribution will be read. Therefore, the second card should contain data as follows: Columns 1 - 12, propellant mass flow rate, lbs_m/sec; columns 13 - 24, total reactor power in megawatts; columns 25 - 36, fuel thermal conductivity, BTU/hr ft $^{\circ}$R; columns 37 - 48, the iteration tolerance, .0001 is suggested; columns 49 - 60, TOTZ as described

above; columns 61 - 72, DIST as described above. It should also be noted that accuracy does not increase if an iteration tolerance smaller than .0001 is used. Less execution time, however, will be required if a larger value such as .001 or .01 is used.

The third card contains only the total number of ordinates that will be used from the fission density distribution curve. This number may appear anywhere in the 1st twelve columns of the card. Normally, the first and as many additional columns as necessary will be used.

Beginning with the fourth card, the values of the ordinates from the local-to-average fission density distribution card will be entered. Six may be entered on each card until all values are included. Only one value should appear in every twelve columns. For example, one value in columns 1 - 12, one value in columns 12 - 24, etc.

When the data cards are ready, the program may be run for exectution. A typical execution deck is seen in Fig. 6. The first card should again be an identification card. The identification card should be followed by an "execute" card. This card and the "data follows" card will vary from one computer installation to another or may not even be required if the program is to be executed on an IBM 1620. Therefore, the "execute" and "data follows" cards should be accomplished as required by the individual facility. The execute card is followed by either the source program deck if compilation is to be in-

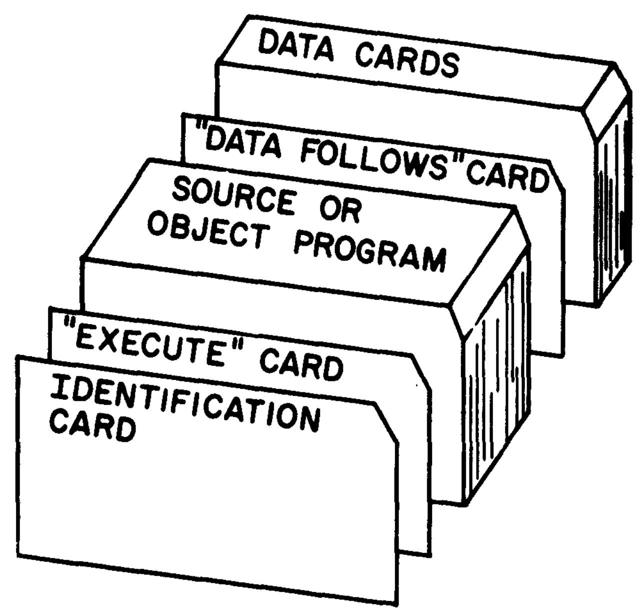

Fig. 6

Correct Sequence of Program
for Execution

cluded or the object program deck if compilation has been completed. The "data follows" card is next, followed by the data cards in the order given previously. As many problems as required may be included, but one complete data deck must be included for each problem. The computer will then read-in more new data upon completion of one problem until no more data is found. On the IBM 7090, the program will exit at this point, but on the IBM 1620, the "Reader-No Feed" light on the console will become illuminated.

The output data consists of a listing of the input quantities, the exit pressure, the exit temperature of the coolant and the maximum material temperature. This is followed by a listing of the coolant pressure and temperature, surface and fuel cell exterior periphery temperature and by increment. Sample output will be found in Appendix D.

Appendix C

A Sample Problem

In this sample problem, values are given for a typical reactor and the local-to-average fission density distribution graph for the reactor power is as shown in Fig. 5.

The optimum propellant weight rate of flow and tube diameter for a maximum of 200 psia pressure deop and a desired output coolant temperature of 3960 °R desired. A maximum reactor temperature of less than 4460 °R.

The reactor length is one foot, the reactor diameter is also one foot and there are 14000 flow tubes. The input temperature of the hydrogen is 400 °R and the input pressure is 1500 psia. The total reactor power is 200 megawatts and the thermal conductivity of the fuel is 80 BTU/hr ft °R. The data from the curve in Fig. 5 is entered and the value for TOTZ is entered on the appropriate card as 30.42, while DIST is 2 (both values in cm). As a trial value, 10 lb_m/sec is used for the propellant mass rate of flow while .003 ft is used for flow tube diameter. From the sample output given in Appendix D, the exit pressure is found to be 1371.0296 psia while the exit temperature is 5408.6960 °R. The maximum material temperature is 5651.2563 °R.

Therefore, another trial value for the mass rate of flow is selected, but this time, the flow tube diameter shall remain the same. The mass rate of flow for this run shall be 17 lb_m/sec. From the second set of output data, the coolant pressure and temperature is found to be 1281.2999 psia and 3607.2389 $^{\circ}$R respectively. While the maximum fuel temperature is 3802.6377 $^{\circ}$R.

A third trial is required with the propellant mass rate of flow equal to 15 lb_m/sec and a flow tube inside diameter of .0029 ft. The results from this computation are found to be an exit pressure of 1270.1448 psia and an exit temperature of 3976.0264 $^{\circ}$R. The maximum fuel temperature is 4174.0162 $^{\circ}$R. This pressure drop is just slightly too great. Therefore, another run with a value of .003 ft for the flow tube diameter and a mass rate of flow of 15 lb_m/sec is selected.

The resultant exit pressure is 1307.2067 psia and the exit temperature is again 3976.0264 $^{\circ}$R. The maximum material temperature achieved at this geometry is 4180.6547 $^{\circ}$R. This meets stated requirements.

The output data for each exectuion run also gives the location of the hot-spot. This may be found by an examination of the pressure and temperatures throughout the length of the reactor are printed.

The output data follows as Appendix D.

Appendix D

Sample Output Data

The pages that follow show how output from the computer program will appear. The sample output data given is from the optimization problem given in Appendix C.

Entrance conditions are printed as the first increment. Exit conditions are found as the last or 101st increment.

A graph of the coolant, surface, and material temperature and the pressure of the coolant, versus length for the fourth execution will be found on page 62. The results displayed by this graph are typical for a nuclear rocket reactor.

ZMAX= 1.000 DIR= 1.000 FT= 14000. DII=0.00300000
PIN = 1500. TIN= 400. W = 10. POW= 200.0000
TKM = 80.00 TOL= 0.0001

PEX= 1371.0296 TEX= 5408.6960 TMAX= 5651.2563

DZ	P	TC	TS	TM
1	1500.0000	400.0000	3211.1358	3287.5305
2	1499.8939	465.5178	3044.0009	3121.4060
3	1499.7680	531.1011	2931.2963	3009.7119
4	1499.6218	597.0633	2844.8815	2924.3074
5	1499.4549	663.5881	2830.9233	2911.3596
6	1499.2668	730.7862	2802.4424	2883.8891
7	1499.0570	798.7196	2790.1908	2872.6479
8	1498.8251	867.2431	2784.6157	2867.8683
9	1498.5706	936.1292	2782.0960	2865.8539
10	1498.2931	1005.3752	2789.6415	2873.9045
11	1497.9923	1074.9688	2809.3551	2894.1233
12	1497.6676	1144.8914	2835.4165	2920.6899
13	1497.3189	1215.1201	2862.3265	2948.1051
14	1496.9457	1285.6297	2894.3066	2980.5905
15	1496.5477	1356.6032	2936.2277	3023.2747
16	1496.1246	1428.0483	2982.5587	3070.4139
17	1495.6760	1499.9351	3031.8707	3120.5343
18	1495.2016	1572.2339	3083.8136	3173.2855
19	1494.7010	1644.9151	3138.0883	3228.3686
20	1494.1739	1717.9502	3194.4378	3285.5263
21	1493.6200	1791.1782	3249.4849	3341.2143
22	1493.0391	1864.2272	3298.1482	3390.0798
23	1492.4310	1937.0789	3348.4405	3440.5741
24	1491.7957	2009.7168	3395.7493	3488.0850
25	1491.1335	2082.1284	3449.5770	3542.1147
26	1490.4439	2154.2983	3504.4604	3597.2003
27	1489.7267	2226.2152	3560.2603	3653.2022
28	1488.9818	2297.7059	3613.3530	3706.2843
29	1488.2094	2368.6960	3665.6509	3758.4813
30	1487.4093	2439.1821	3718.5049	3811.2342

DZ	P	TC	TS	TM
31	1486.5818	2509.1619	3771.8167	3864.4449
32	1485.7267	2578.6344	3825.5011	3918.0283
33	1484.8442	2647.5995	3879.4826	3971.9088
34	1483.9342	2716.0106	3932.7250	4024.9860
35	1482.9970	2783.5470	3979.5300	4071.1848
36	1482.0326	2850.2179	4026.3285	4117.3771
37	1481.0413	2916.0327	4073.0595	4163.5018
38	1480.0232	2981.0015	4119.6702	4209.5062
39	1478.9787	3045.1344	4166.1142	4255.3440
40	1477.9078	3108.4418	4212.3518	4300.9754
41	1476.8108	3171.0524	4260.6909	4348.8757
42	1475.6878	3233.0700	4310.6993	4398.5809
43	1474.5390	3294.5015	4360.5211	4448.0996
44	1473.3644	3355.3540	4410.1379	4497.4133
45	1472.1642	3415.6347	4459.5333	4546.5055
46	1470.9384	3475.3507	4508.6929	4595.3620
47	1469.6873	3534.5092	4557.6042	4643.9703
48	1468.4108	3592.9838	4603.6471	4689.5124
49	1467.1092	3650.7808	4649.2805	4734.6406
50	1465.7826	3707.9098	4694.5525	4779.4074
51	1464.4312	3764.3801	4739.4548	4823.8046
52	1463.0551	3820.2010	4783.9805	4867.8250
53	1461.6545	3875.3815	4828.1235	4911.4628
54	1460.2296	3929.7972	4869.2997	4951.9302
55	1458.7804	3983.2625	4906.1995	4987.8196
56	1457.3074	4035.7912	4942.4828	5023.0925
57	1455.8106	4087.3966	4978.1450	5057.7443
58	1454.2908	4138.0916	5013.1872	5091.7711
59	1452.7478	4187.8888	5047.5913	5125.1698
60	1451.1821	4236.8006	5081.3706	5157.9387
61	1449.5938	4285.1038	5119.5975	5195.5737
62	1447.9832	4332.8607	5158.4332	5233.9042
63	1446.3504	4380.0773	5196.8706	5271.3364
64	1444.6955	4426.7615	5234.9116	5309.3721
65	1443.0186	4472.9202	5272.5569	5346.5123

DZ	P	TC	TS	TM
66	1441.3198	4518.5597	5309.8079	5383.2581
67	1439.5994	4563.5286	5343.6385	5416.3271
68	1437.8573	4607.3726	5368.0978	5439.2708
69	1436.0942	4650.1056	5391.6929	5461.3502
70	1434.3102	4691.7408	5414.4236	5482.5654
71	1432.5059	4732.2909	5436.2911	5502.9173
72	1430.6815	4771.7682	5457.2966	5522.4071
73	1428.8375	4810.1846	5477.4413	5541.0363
74	1426.9742	4847.3455	5492.8109	5554.5471
75	1425.0921	4883.1671	5505.3195	5565.0350
76	1423.1917	4917.6627	5516.7330	5574.4277
77	1421.2734	4950.8451	5527.0519	5582.7258
78	1419.3379	4982.7263	5536.2766	5589.9296
79	1417.3855	5013.3177	5544.4078	5596.0400
80	1415.4168	5042.6616	5552.0334	5601.6976
81	1413.4322	5071.0338	5563.6038	5611.7524
82	1411.4322	5098.4420	5574.3309	5620.9639
83	1409.4170	5124.8934	5584.2166	5629.3339
84	1407.3870	5150.3950	5593.2626	5636.8644
85	1405.3426	5174.9536	5601.4708	5643.5569
86	1403.2841	5198.5754	5608.8427	5649.4132
87	1401.2120	5221.1114	5612.4691	5651.2563
88	1399.1265	5242.4308	5612.5540	5649.3205
89	1397.0282	5262.5406	5611.5536	5646.2993
90	1394.9177	5281.4476	5609.4680	5642.1929
91	1392.7953	5299.1578	5606.2973	5637.0013
92	1390.6615	5315.6771	5602.0415	5630.7247
93	1388.5170	5331.0107	5596.7002	5623.3626
94	1386.3620	5345.1636	5590.2729	5614.9145
95	1384.1973	5358.1402	5582.7590	5605.3798
96	1382.0231	5369.9446	5574.1575	5594.7575
97	1379.8401	5380.5807	5564.4675	5583.0468
98	1377.6487	5390.0516	5553.6876	5570.2460
99	1375.4494	5398.3602	5541.8163	5556.3539
100	1373.2428	5404.9029	5517.7168	5529.1713
101	1371.0296	5408.6960	5473.9448	5480.5879

ZMAX= 1.000 DIR= 1.000 FT= 14000. DII=0.00300000
PIN = 1500. TIN= 400. W = 17. POW= 200.0000
TKM = 80.00 TOL= 0.0001

PEX= 1281.2999 TEX= 3607.2389 TMAX= 3802.6377

DZ	P	TC	TS	TM
1	1500.0000	400.0000	1993.7795	2070.1743
2	1499.7243	438.8127	1966.8111	2044.2162
3	1499.4182	477.7484	1952.2741	2030.6896
4	1499.0810	516.9051	1945.9109	2025.3368
5	1498.7123	556.3523	1940.7992	2021.2355
6	1498.3116	596.1432	1941.9275	2023.3743
7	1497.8782	636.3161	1971.3899	2053.8470
8	1497.4115	676.7951	1980.3938	2063.6464
9	1496.9110	717.4607	1987.7957	2071.5536
10	1496.3762	758.3283	1998.8736	2083.1367
11	1495.8067	799.4087	2013.1241	2097.8923
12	1495.2021	840.7088	2030.1389	2115.4124
13	1494.5618	882.2325	2049.5812	2135.3598
14	1493.8854	923.9814	2071.1699	2157.4537
15	1493.1725	966.0797	2098.7196	2185.7665
16	1492.4225	1008.5474	2128.8837	2216.7389
17	1491.6348	1051.3811	2161.8341	2250.4977
18	1490.8086	1094.5765	2196.0491	2285.5210
19	1489.9433	1138.1281	2231.4314	2321.7116
20	1489.0383	1182.0300	2267.8956	2358.9841
21	1488.0930	1226.1949	2299.7895	2391.5190
22	1487.1070	1270.4052	2328.3119	2420.2434
23	1486.0798	1314.6547	2357.9008	2450.0344
24	1485.0112	1358.9371	2388.4526	2480.7883
25	1483.9008	1403.2458	2419.8748	2512.4126
26	1482.7485	1447.5746	2452.0856	2544.8255
27	1481.5539	1491.9173	2485.0121	2577.9540
28	1480.3166	1536.1667	2515.9784	2608.9098
29	1479.0367	1580.2746	2546.4478	2639.2781
30	1477.7138	1624.2364	2577.4519	2670.1812

DZ	P	IC	IS	TM
31	1476.3479	1668.0477	2608.9318	2701.5601
32	1474.9388	1711.7042	2640.8334	2733.3606
33	1473.4866	1755.2021	2673.1093	2765.5355
34	1471.9909	1798.5079	2704.9922	2797.2533
35	1470.4518	1841.4126	2732.2439	2823.8987
36	1468.8694	1883.9153	2759.6992	2850.7478
37	1467.2437	1926.0152	2787.3118	2877.7542
38	1465.5751	1967.7121	2815.0409	2904.8770
39	1463.8635	2009.0060	2840.3086	2929.5385
40	1462.1103	2049.8969	2868.4729	2957.0965
41	1460.3144	2090.4624	2898.3838	2986.5685
42	1458.4758	2130.7644	2929.7050	3017.5866
43	1456.5945	2170.8025	2961.0471	3048.6255
44	1454.6706	2210.5766	2992.3927	3079.6681
45	1452.7039	2250.0867	3023.7265	3110.6988
46	1450.6946	2289.3330	3055.0341	3141.7032
47	1448.6425	2328.3157	3086.3028	3172.6688
48	1446.5478	2366.9468	3115.5860	3201.4514
49	1444.4104	2405.2255	3144.7146	3230.0747
50	1442.2305	2443.1535	3173.7196	3258.5745
51	1440.0081	2480.7325	3202.5904	3286.9401
52	1437.7434	2517.9641	3231.3174	3315.1620
53	1435.4364	2554.8504	3259.8918	3343.2312
54	1433.0872	2591.3036	3286.3961	3369.0266
55	1430.6960	2627.1945	3309.8675	3391.4876
56	1428.2631	2662.5271	3333.0250	3413.6347
57	1425.7887	2697.3057	3355.8594	3435.4587
58	1423.2733	2731.5346	3378.3626	3456.9515
59	1420.7170	2765.2178	3400.5271	3478.1056
60	1418.1203	2798.3595	3422.3466	3498.9147
61	1415.4833	2831.1440	3447.5684	3523.5446
62	1412.8062	2863.6109	3473.3335	3548.8045
63	1410.0891	2895.7623	3498.8916	3573.8574
64	1407.3320	2927.6004	3524.2404	3598.7010
65	1404.5350	2959.1273	3549.3779	3623.3333

DZ	P	TC	TS	TM
66	1401.6981	2990.3453	3574.3022	3647.7524
67	1398.8214	3021.1480	3596.7771	3669.4657
68	1395.9050	3051.2211	3612.4181	3683.5911
69	1392.9494	3080.5703	3627.5275	3697.1849
70	1389.9552	3109.2011	3642.1007	3710.2425
71	1386.9228	3137.1192	3656.1343	3722.7604
72	1383.8528	3164.3298	3669.6248	3734.7353
73	1380.7456	3190.8383	3682.5693	3746.1643
74	1377.6018	3216.5074	3692.0803	3753.8166
75	1374.4220	3241.2761	3699.5759	3759.2914
76	1371.2069	3265.1505	3706.3579	3764.0526
77	1367.9573	3288.1367	3712.4226	3768.0964
78	1364.6740	3310.2403	3717.7668	3771.4198
79	1361.3576	3331.4669	3722.3876	3774.0198
80	1358.0089	3351.8434	3726.7140	3776.3782
81	1354.6286	3371.5597	3734.0144	3782.1631
82	1351.2172	3390.6193	3740.7525	3787.3855
83	1347.7752	3409.0260	3746.9273	3792.0447
84	1344.3032	3426.7831	3752.5385	3796.1403
85	1340.8016	3443.8938	3757.5852	3799.6714
86	1337.2709	3460.3615	3762.0671	3802.6377
87	1333.7116	3476.0808	3763.8449	3802.6322
88	1330.1245	3490.9592	3763.0740	3799.8405
89	1326.5101	3505.0002	3761.5625	3796.3082
90	1322.8694	3518.2072	3759.3089	3792.0338
91	1319.2030	3530.5835	3756.3114	3787.0155
92	1315.5117	3542.1320	3752.5685	3781.2517
93	1311.7963	3552.8553	3748.0783	3774.7408
94	1308.0576	3562.7563	3742.8394	3767.4810
95	1304.2963	3571.8370	3736.8499	3759.4707
96	1300.5132	3580.0997	3730.1081	3750.7081
97	1296.7092	3587.5464	3722.6122	3741.1914
98	1292.8850	3594.1787	3714.3603	3730.9187
99	1289.0414	3599.9983	3705.3505	3719.8881
100	1285.1793	3604.5815	3687.4198	3698.8744
101	1281.2999	3607.2389	3655.1403	3661.7833

ZMAX= 1.000 DIR= 1.000 FI= 14000. DII=0.00290000
PIN = 1500. TIN= 400. W = 15. POW= 200.0000
TKM = 80.00 TOL= 0.0001

PEX= 1270.1448 TEX= 3976.0264 TMAX= 4174.0162

DZ	P	TC	TS	TM
1	1500.0000	400.0000	2154.9448	2234.3874
2	1499.7411	443.9229	2112.6907	2193.1840
3	1499.4496	487.9580	2088.0660	2169.6100
4	1499.1253	532.2366	2071.8063	2154.4010
5	1498.7673	576.8488	2061.0691	2144.7145
6	1498.3752	621.8605	2082.8533	2167.5495
7	1497.9482	667.3171	2090.2008	2175.9476
8	1497.4856	713.1328	2098.4086	2184.9827
9	1496.9869	759.1709	2105.6807	2192.7802
10	1496.4515	805.4467	2117.4811	2205.1059
11	1495.8789	851.9693	2133.1476	2221.2978
12	1495.2686	898.7437	2152.1470	2240.8225
13	1494.6202	945.7707	2174.0451	2263.2460
14	1493.9330	993.0490	2198.4840	2288.2102
15	1493.2067	1040.7160	2231.1907	2321.7105
16	1492.4403	1088.7907	2266.7239	2358.0842
17	1491.6333	1137.2661	2303.8562	2396.0571
18	1490.7848	1186.1341	2342.4478	2435.4893
19	1489.8944	1235.3854	2378.5342	2472.4163
20	1488.9614	1285.0103	2417.7924	2512.5151
21	1487.9851	1334.9075	2455.8606	2551.2497
22	1486.9651	1384.8288	2488.8763	2584.4756
23	1485.9009	1434.7654	2523.0537	2618.8631
24	1484.7923	1484.7081	2558.2708	2654.2903
25	1483.6390	1534.6485	2594.4201	2690.6497
26	1482.4407	1584.5781	2631.4069	2727.8467
27	1481.1971	1634.4889	2669.1470	2765.7969
28	1479.9079	1684.2595	2704.8493	2801.4883
29	1478.5729	1733.8353	2740.0237	2836.5576
30	1477.1921	1783.2108	2775.7350	2872.1638

DZ	P	TC	TS	TM
31	1475.7653	1832.3810	2811.9173	2908.2411
32	1474.2925	1881.3411	2848.5111	2944.7298
33	1472.7734	1930.0872	2885.4639	2981.5775
34	1471.2081	1978.5819	2921.9756	3017.9175
35	1469.5964	2026.5919	2950.9195	3046.2309
36	1467.9397	2074.1173	2983.1359	3077.8169
37	1466.2368	2121.1583	3015.4492	3109.4998
38	1464.4880	2167.7156	3047.8166	3141.2368
39	1462.6934	2213.7905	3080.2000	3172.9897
40	1460.8531	2259.3842	3112.5656	3204.7249
41	1458.9673	2304.5840	3146.6941	3238.3970
42	1457.0361	2349.4599	3182.2415	3273.6293
43	1455.0596	2394.0125	3217.7655	3308.8380
44	1453.0376	2438.2423	3253.2480	3344.0054
45	1450.9703	2482.1503	3288.6737	3379.1158
46	1448.8577	2525.7375	3324.0280	3414.1549
47	1446.6997	2569.0052	3359.2980	3449.1097
48	1444.4963	2611.8565	3392.4552	3481.7462
49	1442.2478	2654.2917	3425.4026	3514.1683
50	1439.9541	2696.3136	3458.1734	3546.4137
51	1437.6155	2737.9251	3490.7574	3578.4723
52	1435.2319	2779.1291	3523.1455	3610.3351
53	1432.8035	2819.9286	3555.3295	3641.9938
54	1430.3303	2860.2277	3585.3100	3671.2371
55	1427.8127	2899.8846	3612.0772	3696.9536
56	1425.2508	2938.9052	3638.4604	3722.2862
57	1422.6451	2977.2954	3664.4513	3747.2263
58	1419.9958	3015.0609	3690.0428	3771.7672
59	1417.3033	3052.2075	3715.2287	3795.9023
60	1414.5679	3088.7407	3740.0033	3819.6262
61	1411.7899	3124.8643	37[illegible].28[illegible]	3847.2882
62	1408.9694	3160.6230	3797.0883	3875.5703
63	1406.1065	3196.0195	3825.6461	3903.6027
64	1403.2013	3231.0570	3853.9521	3931.3835
65	14[illegible].2538	3265.7384	3882.0051	3958.9111

DZ	P	TC	TS	TM
66	1397.2640	3300.0667	3909.8038	3986.1844
67	1394.2320	3333.9258	3935.0128	4010.6014
68	1391.1580	3366.9710	3953.0460	4027.0585
69	1388.0425	3399.2095	3970.4690	4042.9055
70	1384.8860	3430.6485	3987.2790	4058.1394
71	1381.6890	3461.2950	4003.4736	4072.7579
72	1378.4521	3491.1558	4019.0505	4086.7587
73	1375.1758	3520.2373	4034.0080	4100.1401
74	1371.8606	3548.3901	4045.3277	4109.5270
75	1368.5072	3575.5479	4054.4855	4116.5833
76	1365.1163	3601.7184	4062.8401	4122.8365
77	1361.6887	3626.9090	4070.3892	4128.2842
78	1358.2252	3651.1269	4077.1306	4132.9242
79	1354.7265	3674.3787	4083.0624	4136.7545
80	1351.1934	3696.6946	4088.6347	4140.2803
81	1347.6266	3718.2831	4097.2708	4147.3403
82	1344.0266	3739.1486	4105.2800	4153.7734
83	1340.3939	3759.2954	4112.6622	4159.5796
84	1336.7291	3778.7278	4119.4174	4164.7587
85	1333.0327	3797.4499	4125.5457	4169.3109
86	1329.3051	3815.4653	4131.0470	4173.2362
87	1325.5469	3832.6594	4133.6815	4174.0162
88	1321.7588	3848.9313	4133.6066	4171.8399
89	1317.9415	3864.2854	4132.7122	4168.8440
90	1314.0958	3878.7257	4130.9969	4165.0274
91	1310.2224	3892.2560	4128.4599	4160.3889
92	1306.3222	3904.8800	4125.0998	4154.9274
93	1302.3960	3916.6010	4120.9155	4148.6417
94	1298.4445	3927.4218	4115.9057	4141.5304
95	1294.4685	3937.3456	4110.0690	4133.5923
96	1290.4688	3946.3746	4103.4039	4124.8258
97	1286.4463	3954.5114	4095.9090	4115.2295
98	1282.4018	3961.7579	4087.5826	4104.8016
99	1278.3360	3968.1160	4078.4229	4093.5405
100	1274.2499	3973.1233	4059.8661	4071.7777
101	1270.1448	3976.0264	4026.1931	4033.1012

ZMAX= 1.000 DIR= 1.000 FT= 14000. DII=0.00300000
PIN = 1500. TIN= 400. W = 15. POW= 200.0000
TKM = 80.00 TOL= 0.0001

PEX= 1307.2067 TEX= 3976.0264 TMAX= 4180.6547

DZ	P	TC	TS	TM
1	1500.0000	400.0000	2219.1427	2295.5374
2	1499.7799	443.9229	2173.1407	2250.5459
3	1499.5323	487.9580	2145.4893	2223.9048
4	1499.2567	532.2366	2126.5544	2205.9803
5	1498.9525	576.8488	2113.3768	2193.8132
6	1498.6193	621.8605	2133.9691	2215.4158
7	1498.2565	667.3171	2139.5861	2222.0432
8	1497.8635	713.1328	2146.1096	2229.3622
9	1497.4398	759.1709	2151.6813	2235.4391
10	1496.9849	805.4467	2161.9669	2246.2299
11	1496.4985	851.9693	2176.2750	2261.0432
12	1495.9800	898.7437	2194.0505	2279.3239
13	1495.4292	945.7707	2214.8402	2300.6188
14	1494.8456	993.0490	2238.2706	2324.5544
15	1494.2287	1040.7160	2270.2674	2357.3144
16	1493.5779	1088.7907	2305.1893	2393.0445
17	1492.8925	1137.2661	2341.7630	2430.4266
18	1492.1721	1186.1341	2379.8436	2469.3155
19	1491.4161	1235.3854	2415.3264	2505.6066
20	1490.6240	1285.0103	2454.0878	2545.1763
21	1489.7953	1334.9075	2491.6170	2583.3465
22	1488.9295	1384.8288	2523.9273	2615.8588
23	1488.0263	1434.7654	2557.4489	2649.5825
24	1487.0856	1484.7081	2592.0546	2684.3903
25	1486.1070	1534.6485	2627.6330	2720.1708
26	1485.0903	1584.5781	2664.0854	2756.8253
27	1484.0354	1634.4889	2701.3246	2794.2665
28	1482.9419	1684.2595	2736.4686	2829.4000
29	1481.8097	1733.8353	2771.0808	2863.9111
30	1480.6388	1783.2108	2806.2612	2898.9905

DZ	P	TC	TS	TM
31	1479.4291	1832.3810	2841.9410	2934.5692
32	1478.1805	1881.3411	2878.0587	2970.5859
33	1476.8930	1930.0872	2914.5591	3006.9853
34	1475.5665	1978.5819	2950.6175	3042.8785
35	1474.2009	2026.5919	2978.8827	3070.5374
36	1472.7973	2074.1173	3010.5485	3101.5971
37	1471.3550	2121.1583	3042.3352	3132.7776
38	1469.8740	2167.7156	3074.1981	3164.0342
39	1468.3544	2213.7905	3106.0975	3195.3273
40	1466.7966	2259.3842	3137.9977	3226.6213
41	1465.2005	2304.5840	3171.7329	3259.9177
42	1463.5663	2349.4599	3206.9455	3294.8271
43	1461.8940	2394.0125	3242.1462	3329.7247
44	1460.1838	2438.2423	3277.3170	3364.5924
45	1458.4355	2482.1503	3312.4413	3399.4136
46	1456.6493	2525.7375	3347.5042	3434.1734
47	1454.8252	2569.0052	3382.4920	3468.8580
48	1452.9633	2611.8565	3415.3162	3501.1815
49	1451.0635	2654.2917	3447.9392	3533.2994
50	1449.1262	2696.3136	3480.3949	3565.2498
51	1447.1513	2737.9251	3512.6723	3597.0221
52	1445.1390	2779.1291	3544.7623	3628.6068
53	1443.0894	2819.9286	3576.6559	3659.9952
54	1441.0027	2860.2277	3606.2955	3688.9260
55	1438.8790	2899.8846	3632.6458	3714.2659
56	1436.7186	2938.9052	3658.6219	3739.2316
57	1434.5218	2977.2954	3684.2149	3763.8142
58	1432.2890	3015.0609	3709.4174	3788.0063
59	1430.0205	3052.2075	3734.2226	3811.8011
60	1427.7166	3088.7407	3758.6245	3835.1926
61	1425.3775	3124.8643	3786.6476	3862.6237
62	1423.0035	3160.6230	3815.2284	3890.6994
63	1420.5945	3196.0195	3843.5637	3918.5295
64	1418.1508	3231.0570	3871.6514	3946.1120
65	1415.6723	3265.7384	3899.4897	3973.4451

DZ	P	TC	TS	TM
66	1413.1592	3300.0667	3927.0775	4000.5276
67	1410.6115	3333.9258	3952.0138	4024.7024
68	1408.0295	3366.9710	3969.5884	4040.7614
69	1405.4136	3399.2095	3986.5606	4056.2180
70	1402.7643	3430.6485	4002.9274	4071.0692
71	1400.0820	3461.2950	4018.6856	4085.3117
72	1397.3674	3491.1558	4033.8329	4098.9435
73	1394.6208	3520.2373	4048.3672	4111.9622
74	1391.8427	3548.3901	4059.1873	4120.9235
75	1389.0338	3575.5479	4067.8140	4127.5294
76	1386.1948	3601.7184	4075.6453	4133.3400
77	1383.3262	3626.9090	4082.6782	4138.3520
78	1380.4289	3651.1269	4088.9104	4142.5634
79	1377.5034	3674.3787	4094.3395	4145.9717
80	1374.5505	3696.6946	4099.4275	4149.0917
81	1371.5709	3718.2831	4107.6882	4155.8369
82	1368.5649	3739.1486	4115.3261	4161.9591
83	1365.5331	3759.2954	4122.3409	4167.4583
84	1362.4760	3778.7278	4128.7324	4172.3342
85	1359.3941	3797.4499	4134.5005	4176.5867
86	1356.2878	3815.4653	4139.6452	4180.2158
87	1353.1575	3832.6594	4141.8674	4180.6547
88	1350.0040	3848.9313	4141.3323	4178.0988
89	1346.8278	3864.2854	4139.9820	4174.7277
90	1343.6297	3878.7257	4137.8154	4170.5403
91	1340.4104	3892.2560	4134.8312	4165.5353
92	1337.1706	3904.8800	4131.0280	4159.7112
93	1333.9109	3916.6010	4126.4045	4153.0669
94	1330.6322	3927.4218	4120.9591	4145.6007
95	1327.3350	3937.3456	4114.6904	4137.3112
96	1324.0202	3946.3746	4107.5970	4128.1970
97	1320.6884	3954.5114	4099.6770	4118.2562
98	1317.3404	3961.7579	4090.9288	4107.4872
99	1313.9769	3968.1160	4081.3504	4095.8880
100	1310.5986	3973.1233	4062.1622	4073.6167
101	1307.2067	3976.0264	4027.5161	4034.1592

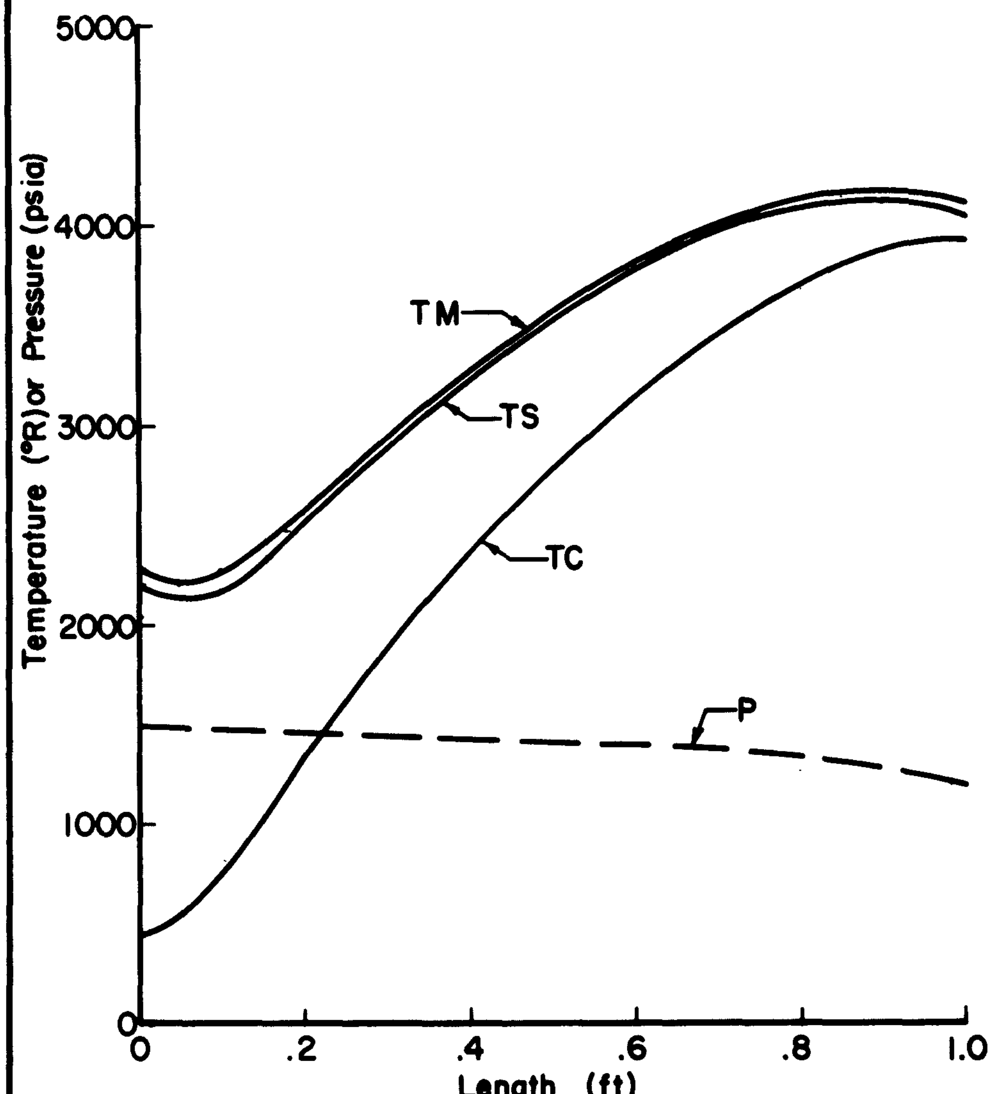

Fig. 7

Results From Sample Problem
(Typical)

Vita

Captain DeMos was born in Chicago, Illinois on January 27, 1930, the son of Mr. and Mrs. Peter K. DeMos. He entered the U. S. Naval Academy at Annapolis, Maryland under a Secretary of the Navy Appointment in 1950. He was graduated with distinction with a Bachelor of Science degree in 1954 and was commissioned a 2nd Lieutenant in the regular Air Force. After serving overseas in Germany, he entered USAF Flying Training in 1957 and received the aeronautical rating of ilot. He was a Military Air Transport Service aircraft commander prior to entering the Graduate Astronautics program at the Air Force Institute of Technology in 1961.

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